

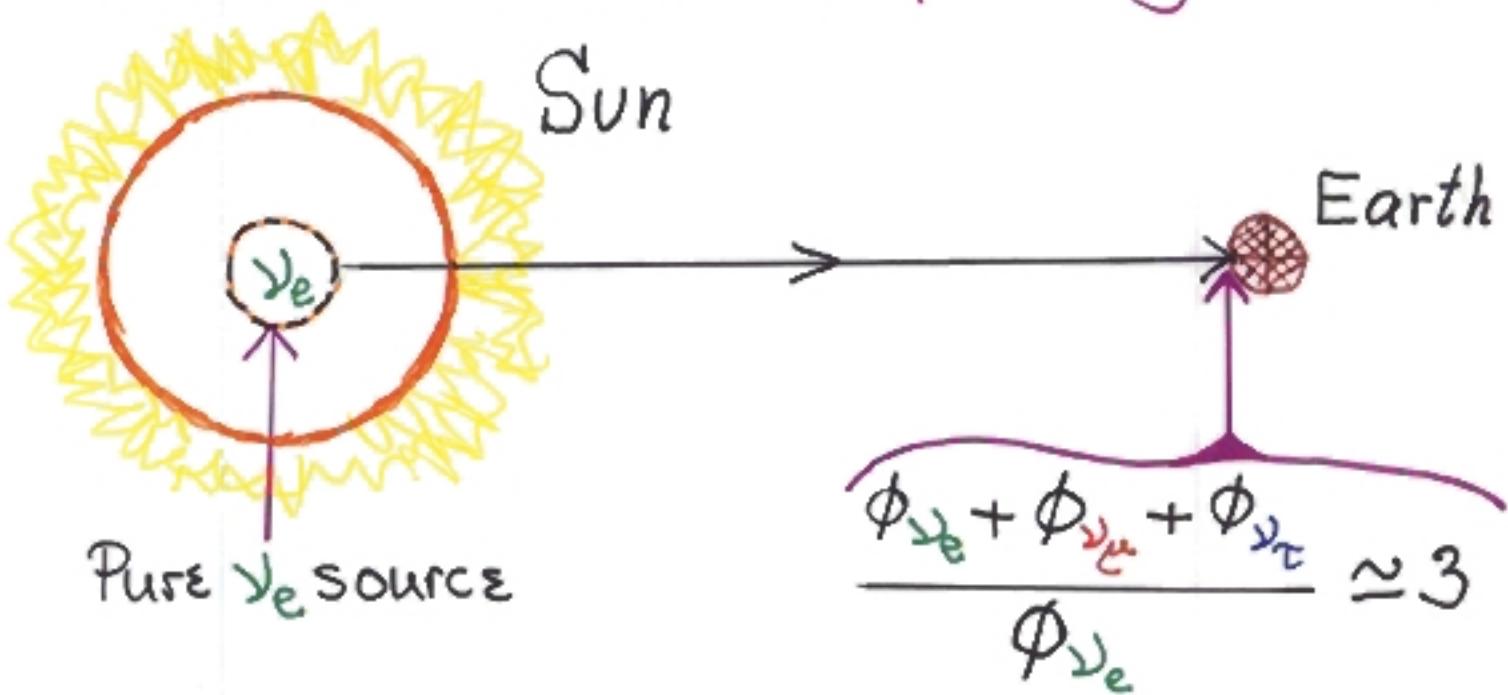
Aspen
Feb. 7, 2004

Exploring the Neutrino World

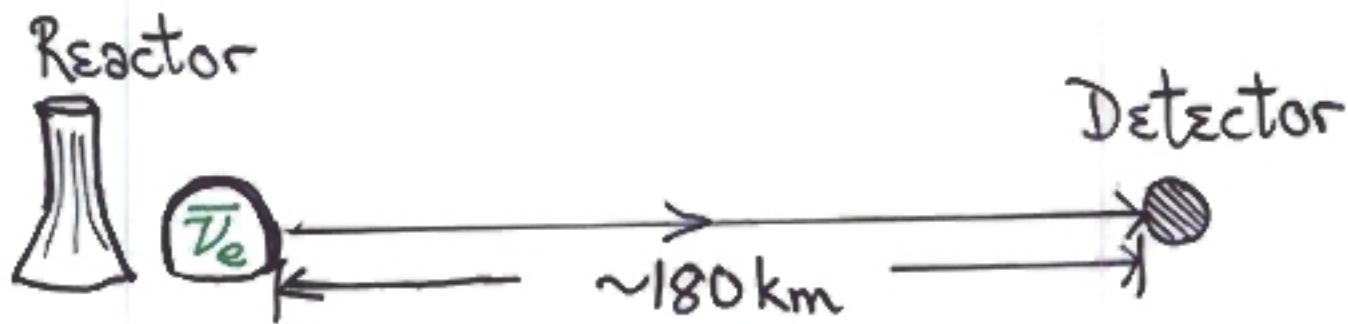
Boris Kayser

Evidence for Flavor Change

Solar Neutrinos: Compelling Evidence



Reactor Neutrinos: Very Strong Evidence



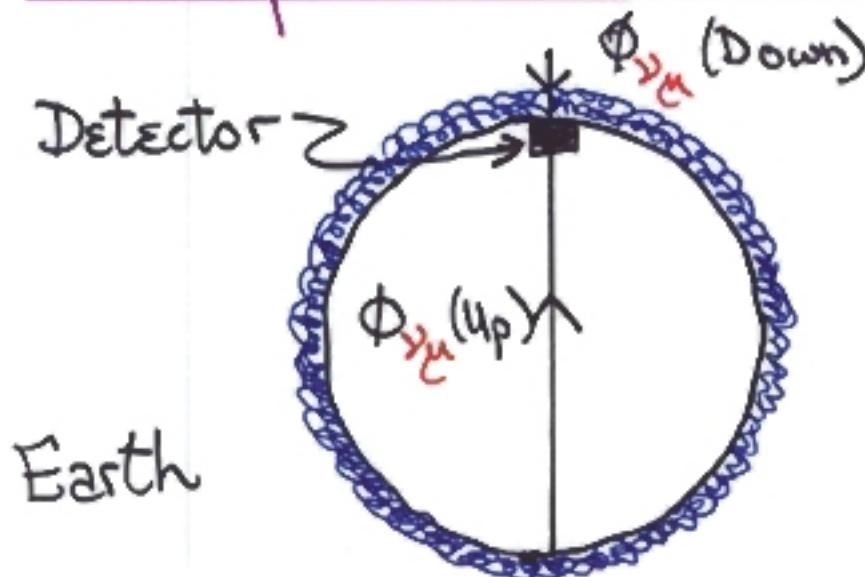
Produced
 $\phi_{\bar{\nu}_e}$

Surviving
 $\simeq 0.6 \phi_{\bar{\nu}_e}$

One pair of parameters fits both solar & reactor data.

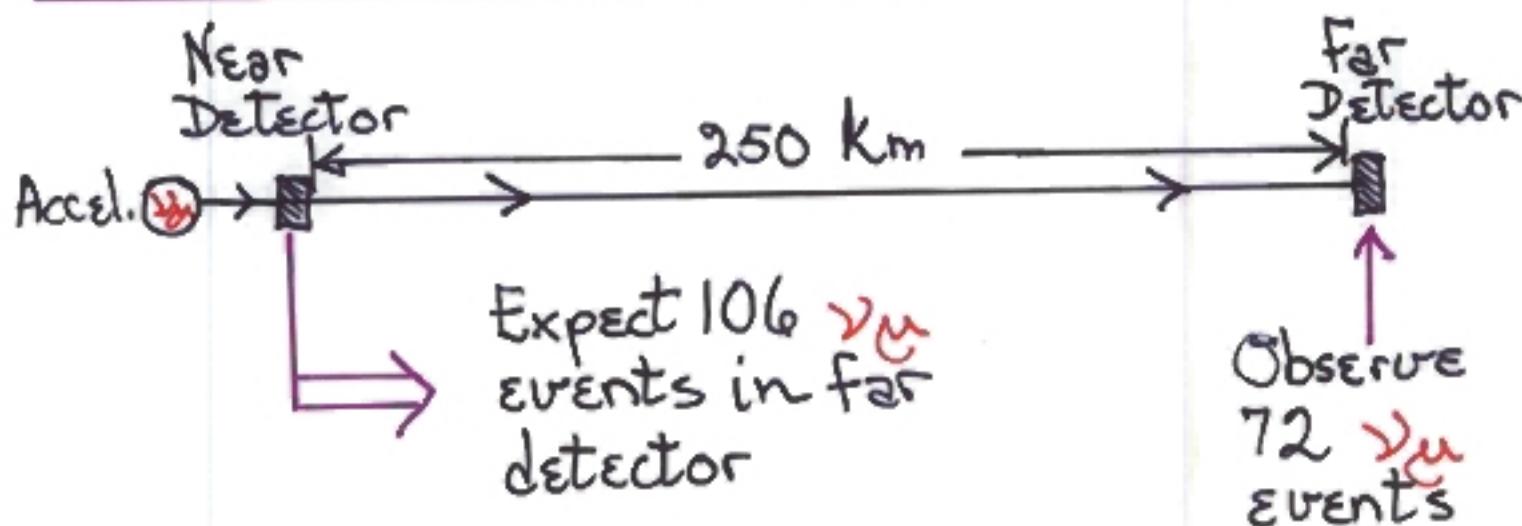
W.2

Atmospheric Neutrinos: Compelling Evidence,



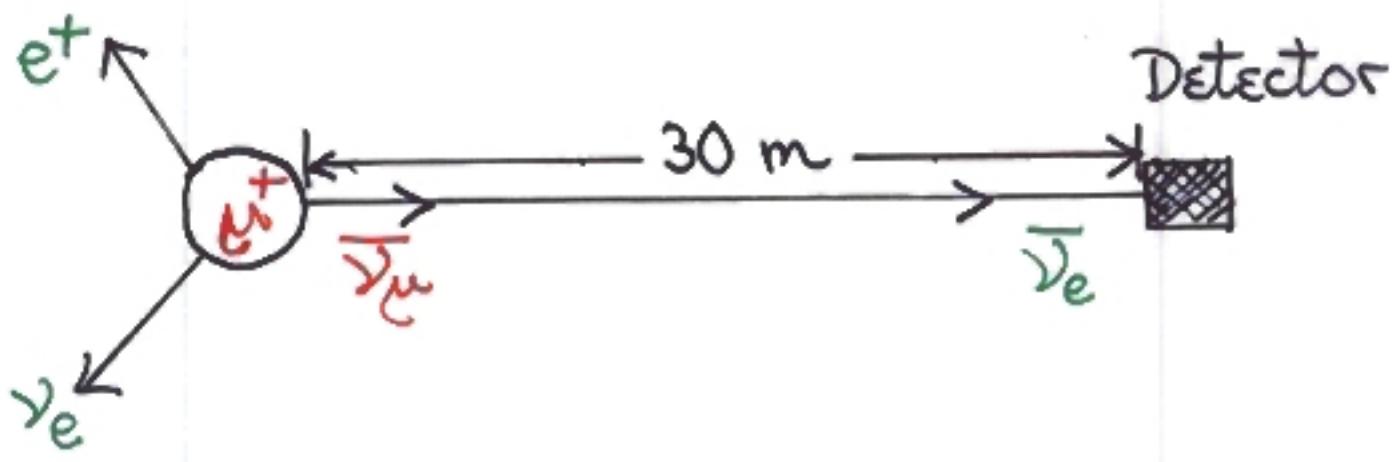
$$\frac{\phi_{\nu_\mu} (\text{Up})}{\phi_{\nu_\mu} (\text{Down})} \approx \frac{1}{2}$$

Accelerator Neutrinos: Interesting Evidence



The hypothesis $\nu_\mu \rightarrow \nu_\tau$ with one pair of parameters fits both the atmospheric and accelerator data.

LSND Neutrinos: Unconfirmed Evidence



H.OI

The observed flavor changes are not due to flavor-changing interactions with matter, but to —
neutrino masses and mixing.

Prob [Atmospheric \rightarrow flavor change]
depends on —

$$\frac{L(\text{Distance } \rightarrow \text{travels})}{E(\rightarrow \text{energy})} .$$

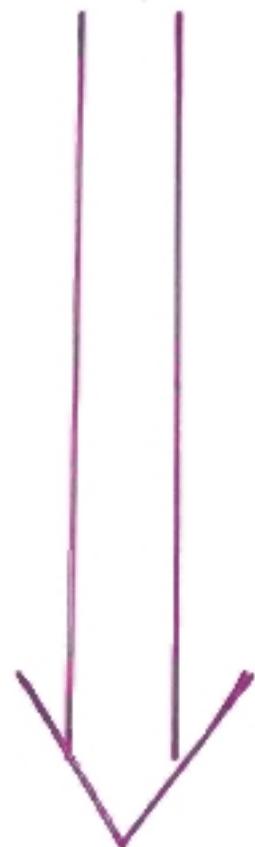
Time elapsed in \rightarrow rest frame during journey

$$= m(\rightarrow \text{mass}) \times \frac{L}{E} .$$

1.41

What questions are raised by the discovery of neutrino mass and mixing?

A sampling



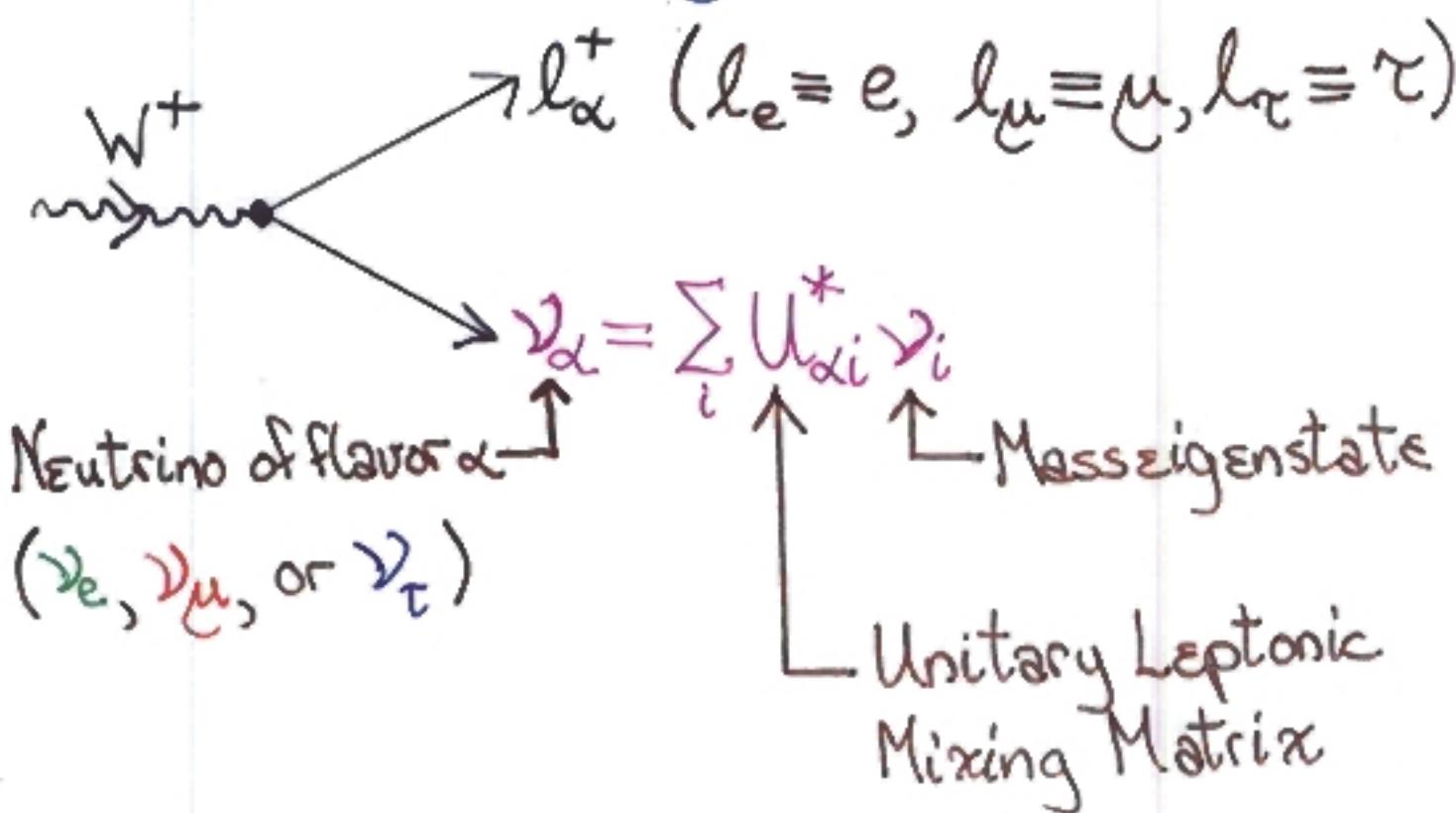
- A.II What Would We Like to Know?
- What physics is responsible for neutrino masses and mixing?
- How many neutrino species are there?
Are there sterile neutrinos?
- What is the neutrino mass spectral pattern?
- What is the scale of neutrino mass?
- Are neutrinos Majorana particles ($\bar{\nu} = \nu$)?
- What is the leptonic mixing matrix?
- Do neutrino interactions violate CP?
- Is leptonic ~~CP~~ responsible for the baryon asymmetry in the universe?

A.2

Are there surprises?

- Rapid ν decay?
 - Non-Standard-Model ν interactions?
 - ???
-

Leptonic Mixing



$$\nu_i = \sum_{\alpha} U_{\alpha i} \nu_{\alpha}$$

$$\text{Flavor-}\alpha \text{ fraction of } \nu_i = |U_{\alpha i}|^2.$$

c.1) What Have We Already Learned?

We do not know how many neutrino mass eigenstates γ_i there are.

Assuming CPT, confirmation of LSND by MiniBooNE would imply there are more than 3.

The reason:

<u>Neutrinos</u>	<u>Required Δm^2 (eV2)</u>
Solar	$10^{-(4-5)}$
Atmospheric	$\sim 10^{-3}$
LSND	~ 1

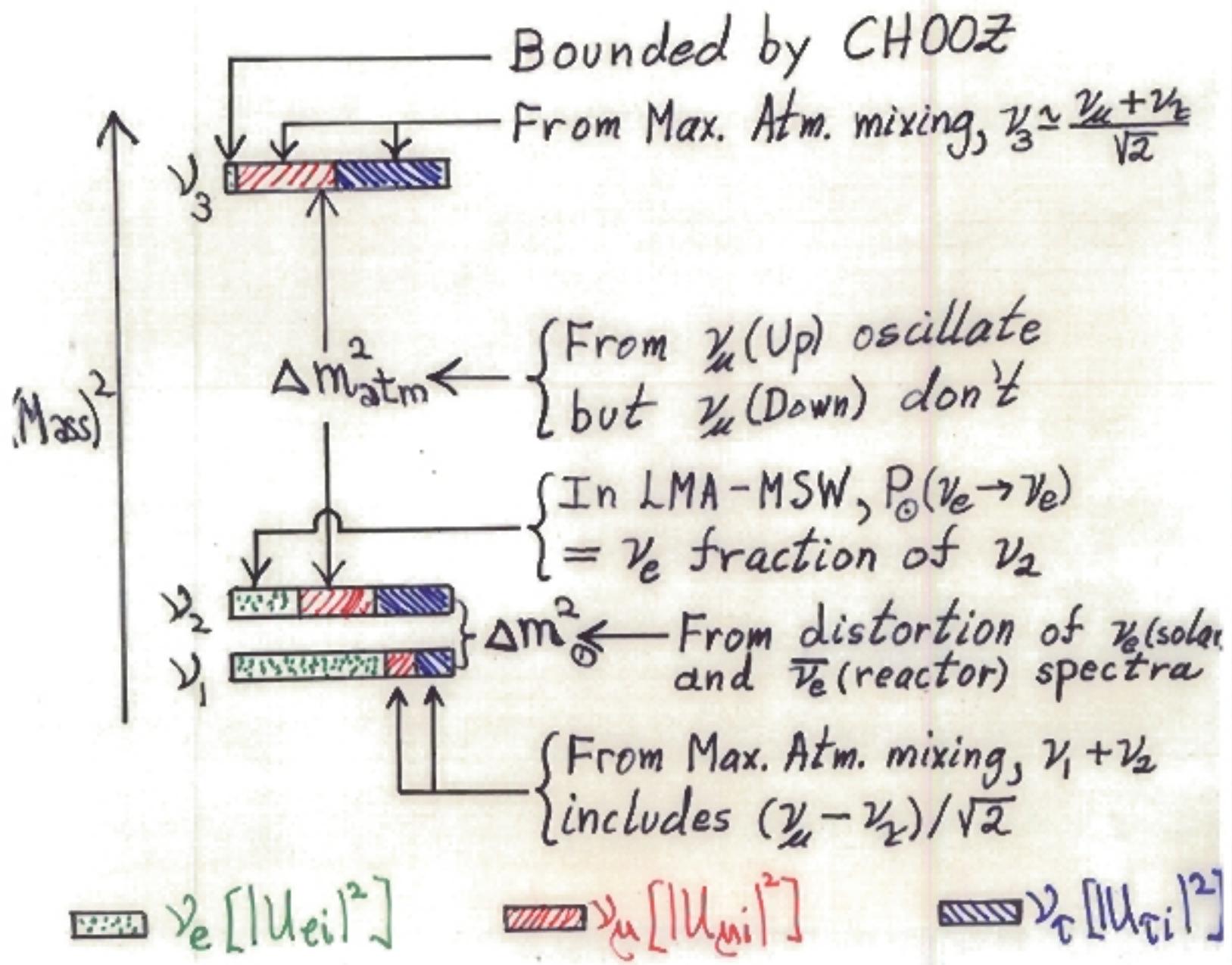
Only 3 neutrinos \Rightarrow (Mass) $^2 \uparrow =$

$$\Rightarrow \Delta m_{\text{LSND}}^2 = \Delta m_{\text{atm}}^2 + \Delta m_{\odot}^2.$$

If LSND is not confirmed, nature may contain only 3 neutrinos.

Then the spectrum looks like $\underline{\underline{\underline{}}}$ or $\underline{\underline{\underline{\underline{}}}}$.

If it is like $\underline{\underline{\underline{\underline{}}}}$:

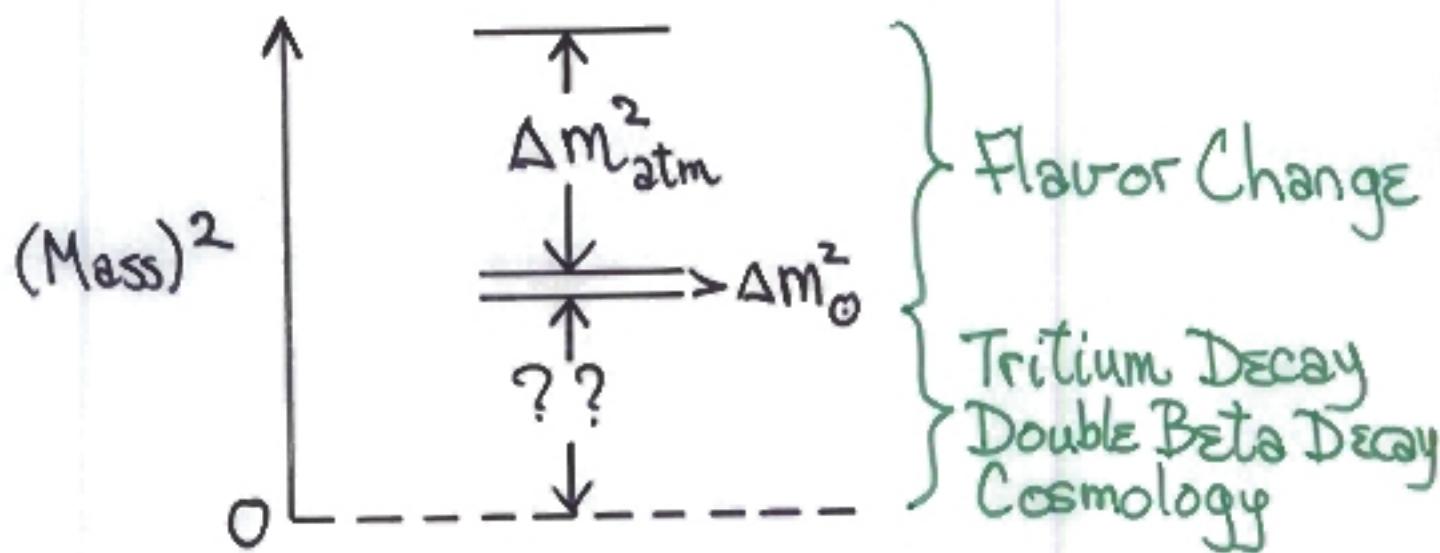


A.7)

The Future — Open Questions

- * How many neutrino species are there?
Do sterile neutrinos exist?
- MiniBooNE

- * What are the masses of the mass eigenstates ν_i ?



Is the spectral pattern $\begin{array}{c} \text{---} \\ \text{---} \end{array}$ or $\begin{array}{c} \text{---} \\ \text{---} \end{array}$?

GUTS: $\begin{array}{c} \text{---} \\ \text{---} \end{array}$ $\begin{array}{c} \text{---} \\ \text{---} \end{array}$: Symmetry
(Albright) (Babu & Mohapatra)

How Δm^2 vs. θ_{13} May Be Determined

We determined that $m(K_L) > m(K_S)$ by —

- Passing kaons through matter (Regenerator)
- Beating the unknown $\text{Sign}[m(K_L) - m(K_S)]$ against the known $\text{Sign}[\text{Regeneration Amp.}]$

We will determine

$$\text{Sign}[m^2(\leftarrow) - m^2(\rightarrow)] = S$$

by —

- Passing neutrinos through matter (Earth)
- Beating the unknown sign S against the known $\text{Sign}[\text{forward } \nu_e e \rightarrow \nu_e e \text{ Amp.}]$

At superbeam energies $E \lesssim 2 \text{ GeV}$,

$$\sin^2 2\theta_{13} [\text{In Earth}] \cong \sin^2 2\theta_{13} \left[\frac{\nu}{\bar{\nu}} \right] S \frac{E}{6 \text{ GeV}}$$

W.5]

The absolute mass scale —

$$0.04 \text{ eV} \lesssim \text{Mass[Heaviest } \nu_i] < 0.23 \text{ eV}$$

$$\sqrt{\Delta m^2_{\text{atm}}} \quad \uparrow$$

(SuperK;
90% CL)

Cosmology

(If 3 neutrinos,
Spergel et al. + assumptions;
95% CL)

* Is each mass eigenstate —

- A Majorana particle ($\bar{\nu}_i = \nu_i$)

or

- A Dirac particle ($\bar{\nu}_i \neq \nu_i$) ?

Quarks and charged leptons are distinguished from their antiparticles by electric charge.

W.b]

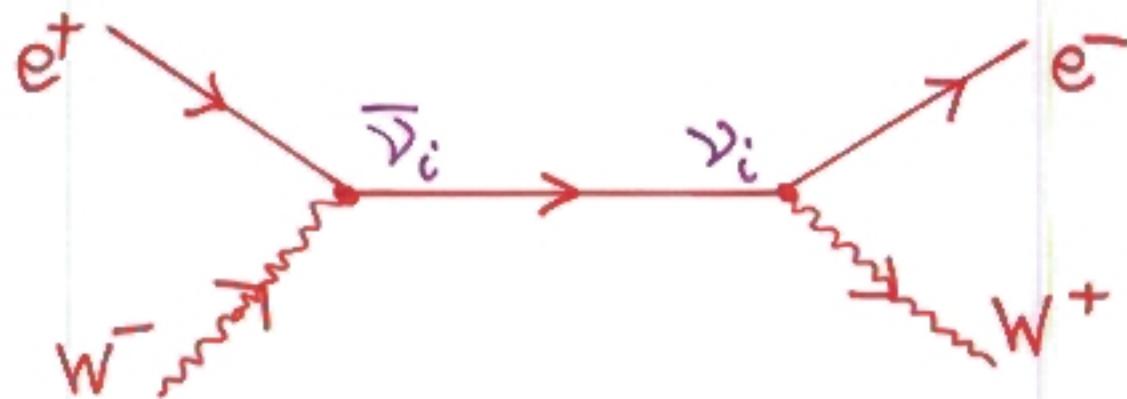
Neutrinos may not carry any conserved charge-like quantum numbers.

A conserved Lepton Number L defined by —

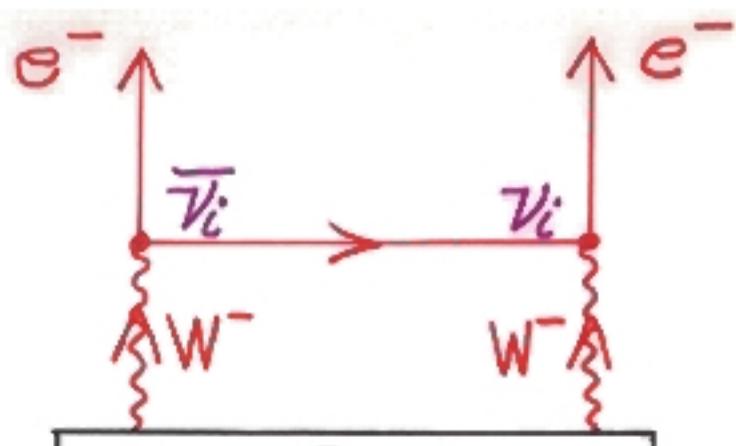
$$L(e) = L(\ell^-) = -L(\bar{\nu}) = -L(\ell^+) = 1$$

may not exist.

If it does not, then we can have —



It is more practical to seek —



$\text{Nucl} \Rightarrow \boxed{\text{Nucl. Process}} \Rightarrow \text{Nucl}'$

Neutrinoless Double Beta Decay

Observation would imply -

$$\bar{\nu}_i = \nu_i \quad \Rightarrow \quad L$$

$$\Rightarrow m \nu \nu \quad \text{Majorana mass term}$$

$$[\text{cf. } m \bar{\nu} \nu \quad \text{Dirac mass term}]$$

Quarks and charged leptons have only Dirac masses.

Majorana ν masses would mean that the physics of ν mass differs qualitatively from that of q and l mass.

* What is the leptonic mixing matrix U ?

For 3 neutrinos -

$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & C_{23} & S_{23} \\ 0 & -S_{23} & C_{23} \end{bmatrix} \times \begin{bmatrix} C_{13} & 0 & S_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -S_{13} e^{i\delta} & 0 & C_{13} \end{bmatrix}$$

$$\times \begin{bmatrix} C_{12} & S_{12} & 0 \\ -S_{12} & C_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \times \begin{bmatrix} e^{i\frac{\alpha_1}{2}} & 0 & 0 \\ 0 & e^{i\frac{\alpha_2}{2}} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Solar

Majorana CP Phases

$$C_{ij} \equiv \cos \Theta_{ij}, \quad S_{ij} \equiv \sin \Theta_{ij}$$

$$\Theta_{23} \approx \Theta_{\text{atm}}, \quad \Theta_{12} \approx \Theta_0$$

$\delta, \alpha_1, \alpha_2$ are CP phases.

Only δ can affect neutrino oscillation.
All effects of δ depend on $\sin \Theta_{13}$.

C4] The 90% CL mixing-angle ranges—

$$\sin^2 2\theta_{\text{atm}} > 0.9 \quad (\text{Super-K})$$

$$0.73 \lesssim \sin^2 2\theta_0 \lesssim 0.92 \quad (\text{SNO})$$

$$\sin^2 2\theta_{13} \lesssim 0.2 \quad (\text{CHOOZ})$$

Clearly, θ_{atm} and θ_0 are large, unlike any quark mixing angles.

But what is θ_{13} ? How small is it??

H.10] How Θ_{13} May Be Measured

$\sin^2 \Theta_{13} = |\mathbf{U}_{e3}|^2$ is the small γ_e piece
of γ_3 . γ_3 is at one end of Δm^2_{atm} .

∴ We need an experiment with L/E sensitive
to Δm^2_{atm} , and involving γ_e .

Possibilities

Reactor $\bar{\gamma}_e$ disappearance while traveling
 $L \sim 1 \text{ km.}$

Accelerator $\gamma_\mu \rightarrow \gamma_e$ or $\gamma_e \rightarrow \gamma_\mu$ while
traveling $L > \text{Several hundred km.}$

W.91

* Do neutrino interactions violate CP?

$$\text{Prob}(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta) = \text{Prob}(\nu_\alpha \rightarrow \nu_\beta; U \rightarrow U^*)$$

δ leads to -

$$\text{Prob}(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta) \neq \text{Prob}(\nu_\alpha \rightarrow \nu_\beta).$$

\uparrow CP

Demonstrating that CP in oscillation is nonzero would establish that CP is not a peculiarity of quarks.

Leptonic CP might have been the CP that made baryogenesis possible.

All

In the See-Saw mechanism, the light neutrinos have very heavy Majorana neutral lepton partners N .

Perhaps in the early universe there was

$$\Gamma[N \rightarrow l^+ + \text{Higgs}^-] > \Gamma[N \rightarrow l^- + \text{Higgs}^+]$$

\uparrow
 CP

(Leptogenesis)

Standard Model ($B-L$) - conserving, but B - and L -violating, processes would then have converted some of this antilepton excess into a baryon excess.

(Fukugita & Yanagida)

F.21

How Is CP in ν Oscillation Related To CP in Leptogenesis?

The relation is model-dependent.

However —

It is not likely that we have one without the other.

(Davidson, Pascoli, Petcov, Rodejohann, Yanagida)
Kitano

To find CP in Oscillation

Compare $\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta$ with $\nu_\alpha \rightarrow \nu_\beta$.

Inspired by the exciting discoveries in neutrino physics,
But keenly aware of the need for a coherent plan for the future,
The American Physical Society Divisions of —

- Particles and Fields
- Nuclear Physics
- Astrophysics
- Physics of Beams

are sponsoring a year-long

STUDY OF THE PHYSICS OF NEUTRINOS

Background information at: www.neutrinooscillation.org/studyaps/

The Purposes of the Study

- Primary Purpose —
To move towards a coherent strategy for answering the open neutrino questions — a clear, unified plan that funding sources can easily consider and promote.

To this end, the study will —

- Identify the most important questions
- Evaluate the physics reach of the proposed ways of answering them
- Examine how different facilities and experiments complement each other
 - Create a decision tree
 - Determine an intelligent sequence of facilities and experiments

Its findings will guide the creation of the future neutrino program.

To quote its Charge —

“The Study will lay scientific groundwork for the choices that must be made during the next few years.”

— Secondary Purpose —

To explain to colleagues in other areas of physics, the funding sources, and the general public why neutrino physics is now so exciting.

The Structure of the Study

Chairmen

Stuart Freedman, Boris Kayser

Organizing Committee

Janet Conrad, Guido Drexlin,
Belen Gavela, Takaaki Kajita,
Paul Langacker, Keith Olive,
Bob Palmer, Georg Raffelt,
Hamish Robertson, Stan Wojcicki
Lincoln Wolfenstein

Working Groups — The Central Element

Each working group is defined by an experimental approach.

The groups, their leaders, and their first meeting —

Solar and Atmospheric Neutrino Experiments

John Bahcall <jnb@ias.edu>, Josh Klein <jrk@physics.utexas.edu>

January 19, by phone

Reactor Neutrino Experiments

Gabriela Barenboim <gabriela@fnal.gov>, Ed Blucher <blucher@hep.uchicago.edu>

February 7-8, Chicago

Superbeam Experiments and Development

Bill Marciano <marciano@bnl.gov>, Doug Michael <michael@hep.caltech.edu>

January 29-30, Fermilab

Neutrino Factory and Beta Beam Experiments and Development

Stephen Geer <sgeer@fnal.gov>, Michael Zisman <mzsisman@lbl.gov>

March 3-4, tentatively at Argonne

Neutrinoless Double Beta Decay and Direct Searches for Neutrino Mass

Steve Elliott <elliotts@lanl.gov>, Petr Vogel <pxv@caltech.edu>

February 27-28, Caltech

What Cosmology/Astrophysics and Neutrino Physics can Teach Each Other

Steve Barwick <barwick@HEP.ps.uci.edu>, John Beacom <beacom@fnal.gov>

February 5, by phone

Theorists participate in all working groups.

They will also discuss issues like how best to use future measurements to discriminate among theoretical models.

Coordinator of theoretical discussions:

Rabi Mohapatra <rmoahapat@physics.umd.edu>

Participation in the study
is warmly encouraged!

To join any working group,
just contact its leaders.

Contact information at -
home.fnal.gov/~boris/NeutrinoStudy2.ppt

Summary

The discovery of ν mass and mixing has raised very interesting questions.

Let's go answer them !
